

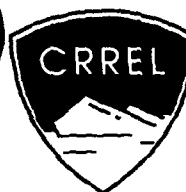
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## Air Tightness Measurement Technique for Multiplex Housing

Stephen N. Flanders

March 1992



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*For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

*COVER: Making air-tightness measurements at Fort Drum, New York.*



**U.S. Army Corps  
of Engineers**  
Cold Regions Research &  
Engineering Laboratory

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## **PREFACE**

This report was prepared by Stephen N. Flanders, Research Civil Engineer, Civil and Geotechnical Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. This report results from research performed under DA Project 4A752784AT42, Budget Package: *Installation Management in Cold Regions*; Functional Area: *Conventional Facilities*; Task: *Installation Operations*; Work Package: *DEH Management*; Work Unit BS018: *Advanced Diagnostic Techniques for Military Building Envelopes in Cold Regions*.

The author thanks the following people: Stephen Rowley of the Directorate of Engineering and Housing at Fort Drum, for providing the facilities and coordination for this study; Robert Davis and Charles Korhonen, both of CRREL, for their technical review of this report; and Mark Hardenberg, for his editorial assistance.

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# Air Tightness Measurement Technique for Multiplex Housing

STEPHEN N. FLANDERS

## INTRODUCTION

This report discusses evaluating the air tightness of multiple-residence buildings, such as townhouses and garden apartments. Standard test method E 779 (ASTM 1987) offers a fan-pressurization technique for measuring air tightness of buildings that can be configured as a single, contiguous zone and is most practical for single-family residences. The E 779 procedure is to obtain a series of readings of air flow ( $Q_i$ ) for each setting of pressure difference ( $\Delta P_i$ ) across the building envelope tried, to determine  $n$  and  $C$  in the following relationship:

$$Q_i = C (\Delta P_i)^n \quad (1)$$

where  $n$  is dimensionless and  $C$  has dimensions of flow/pressure <sup>$n$</sup> .

Fan size usually limits E 779 to buildings of modest size, while the presence of party walls that may permit leakage to adjacent indoor zones limits E 779 to single-zone buildings. With  $C$  and  $n$  in hand, it is possible to calculate the area of an orifice that would have an air leakage equivalent to that from all of the cracks in the building at a designated  $\Delta P$ . This equivalent leakage area is the measure of building tightness favored in this study and is derived as  $L$  below.

The U.S. Army has many attached family housing units. These may be duplexes, townhouses (two-story residences that share common walls) or garden apartments (two-story buildings wherein each residence is on a single floor and shares a common floor or ceiling, as well as walls). Several hundred units of family housing units were recently built at Fort Drum, New York, where there were many occupant complaints about cold drafts. The purpose of this study was to establish a technique that could measure the tightness of

these dwellings and compare the good with the bad.

Techniques were tried both to determine the equivalent leakage area ( $L$ ) of the exterior building envelope and to determine  $L$  for party construction between dwellings. The basic approach for determining  $Q$  and  $L$  for the exterior envelope was to pressurize adjacent attached dwellings simultaneously, so that there would be no air exchange between them. For determining  $Q$  and  $L$  for party walls and floors, two techniques were tried: determining the difference between  $L$  with no lateral flow into adjacent areas and then  $L$  with lateral flow, and using two apparatuses in concert to create specific  $\Delta P$  values across the party construction and measuring the resulting air flow from those  $\Delta P$  values.

This paper discusses: 1) calculating crack area  $L$ , 2) confidence limits on  $Q$  and  $L$ , 3) bias between pressurization and depressurization, 4) measurement protocol for calculating the  $L$  of the total envelope of a multizone building, 5) measurement protocol for calculating the  $L$  of party walls or floors, and 6) field measurements of multi-dwelling buildings at at Fort Drum, New York.

## CALCULATING CRACK AREA

The question of an appropriate means for characterizing the size of cracks is open for disagreement. The objective is to define the equivalent-sized orifice that would permit the same flow rate ( $Q$ ) at the same difference in pressure across the building envelope ( $\Delta P$ ) as occurred in the building. E 779 calculates this effective leakage area by

$$L = C (\Delta P)^{(n-1/2)} (\delta/2)^{1/2} \quad (2)$$

where  $\delta$  is the density of air. Equation 2 is the equivalent of eq 1 times a constant, that is

$$L = Q / k \quad (2a)$$

$$k = (\delta / 2 \Delta P)^{1/2} \quad (2b)$$

where  $\Delta P$  is a defined value in eq 2 and 2b. E 779 recommends 4 Pa as a conventional  $\Delta P$ . The proposed Canadian standard is similar, except that it introduces Kirschhoff's discharge coefficient,  $K = 0.61$ , so that the Canadian effective leakage area is calculated from eq 2 as

$$CEL = L / K \quad (3)$$

where  $\Delta P$  is 10 Pa.

The E 779-recommended  $\Delta P$  of 4 Pa is in the range of naturally occurring values, but is well below the range of E 779 experimental practice, which starts at 12.5 Pa and increases to 75 Pa in 12.5-Pa increments. The further a calculated value of  $Q$  occurs from the mean of the experimental  $\Delta P$  values, the greater is the statistical uncertainty. To characterize the comparative importance of holes in party walls and floors with those in exterior walls in this study, 4 Pa was chosen as a value for use in eq 2, although this was out of the range of the  $\Delta P$  values used in the measurements. The confidence limits for this value proved acceptable.

## PRECISION AND BIAS IN FLOW AND EQUIVALENT LEAKAGE AREA CALCULATIONS

Persily and Grot (1985) addressed the question of accuracy in obtaining  $n$  and  $C$  for eq 1 from fan pressurization data, both experimentally and statistically. Their results show predictive uncertainties as a percentage of predicted airflow to range between 1.1 and 15%. In general, more pairs of measured  $\Delta P$  and  $Q$  data meant lower uncertainties. Likewise, predictions of  $Q$  at 25 and 50 Pa resulted in lower uncertainties.

### Confidence intervals

Discussions of precision must address standard statistical assumptions, which Persily and Grot chose not to discuss in their paper. First, we must include an error term in eq 1 as follows

$$Q = \partial C (\Delta P)^n \quad (4)$$

where  $\partial$  is an error term. The values of  $n$  and  $C$  are estimated by taking the natural logarithm of eq 4 and

performing a linear regression on the following transformed model

$$Y_i = a + b C_i + \epsilon_i \quad (5)$$

where

$$Y_i = \ln Q_i$$

$$C_i = \ln \Delta P_i$$

$$a = \ln C$$

$$b = n$$

$$\epsilon_i = \ln \partial_i$$

$$i = 1, \dots, N.$$

E 779 requires both positive and negative modes of pressurization. For each mode it suggests six sets of pressure difference and flow data, based on 12.5-Pa increments in  $\Delta P$ , starting at 12.5 Pa up to 75 Pa. It recognizes that the full range may not be achievable, and requires at least five data sets.

We want to know whether the measurement process is precise enough for five or six data sets to suffice. The following discussion of the statistics obtained is based on Draper and Smith (1966), the same source used by Persily and Grot. In the transformed logarithmic domain, one must examine the underlying assumptions that  $\epsilon_i = N(0, \sigma^2)$ , i.e.

1.  $\epsilon_i$  is a random variable with mean zero and variance  $\sigma^2$ .

2.  $\epsilon_i$  and  $\epsilon_j$  are uncorrelated.

3.  $\epsilon_i$  is normally distributed.

Since  $\epsilon_i$  is in the transformed domain of eq 5, it is important that the experimenter check these assumptions with a plot of  $\epsilon_i$ . Inspection of the residuals of experimental versus model results, depicted as a percentage of the model in Figure 1, demonstrates that the assumption that  $\epsilon_i$  is normally distributed is a plausible one.

Assume that the assumptions about  $\epsilon_i$  have been met. Then a linear regression will give  $A$ ,  $B$  and  $\hat{Y}$  as estimates of  $a$ ,  $b$  and  $Y_i$

$$\hat{Y} = A + B X. \quad (6)$$

The regression has an estimate  $s$  of  $\sigma$ , based on  $N - 2$  degrees of freedom

$$s^2 = \frac{\sum_{i=1}^N (Y_i - \hat{Y}_i)^2}{(N - 2)}. \quad (7)$$

As is given in Draper and Smith, the 95% confidence interval about a given  $Y_k$  is yielded by

$$CI_k = t(N - 2, 0.975) \left( 1 + \frac{1}{N} + \frac{(X_k - \bar{X})^2}{\sum_{i=1}^N (X_i - \bar{X})^2} \right)^{1/2} s \quad (8)$$

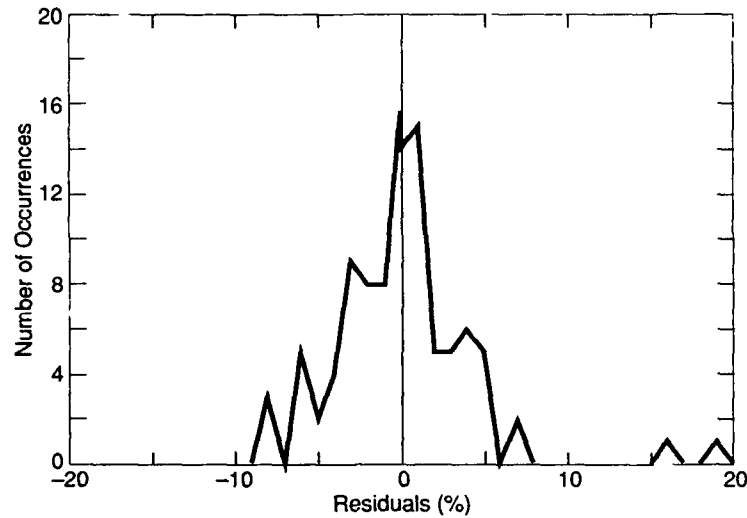


Figure 1. Residuals of  $\ln \hat{Q}$  versus  $\ln Q$  as a percentage of  $\ln \hat{Q}$  for 16 fan pressurization tests.

where  $t(N-2, 0.975)$  is a  $t$ -distribution value for 95% confidence and  $N$  points

$$\bar{X} = \text{Mean}_1 \text{ of } X_N \dots X_1$$

So, the expression

$$\hat{Y} - CI_k < Y_k < \hat{Y} + CI_k \quad (8a)$$

is 95% likely to be true. Translating back into the domain of eq 1, we have

$$\hat{Q} / \exp(CI_k) < Q_k < \hat{Q} \cdot \exp(CI_k). \quad (8b)$$

This can be seen for three sets of test pressures in Table 1.

We can see from the example given in Table 1 that for some plausible values of  $s$ , the uncertainty about the value of a given point is only a few percentage points. This effect is fairly uniform within the range of  $\Delta P$  measurements prescribed by E 779. Also, a  $\pm 5\%$  additive error in the logarithmic domain translates as an approximately  $\pm 5\%$  additive error in the original domain. Table 1 suggests that the choice of  $\Delta P$  has only a minor effect on the confidence limits of the measurement.

A computer simulation can demonstrate the effects of experimental errors and the number of runs on obtaining accurate values of  $n$  and  $C$  in eq 1. We can choose values for  $n$  and  $C$  and know the correct value of  $Q$  for each  $\Delta P$ . If we assume a normally distributed error in reading  $Q$ , then we obtain  $Q_{\text{exp}}$  as the basis for per-

Table 1. Confidence limits at 95% for standard E 779 pressure differences. The estimate,  $s = 0.013$ , of  $\sigma$  is used as an example to obtain specific values of  $CI$ . Otherwise, one would multiply the experimentally obtained value of  $s$  times the corresponding  $CI/s$  in the second column to obtain  $CI$ .

| $\Delta P$  | $CI/s$ | $CI$  | $\exp(CI)$ |
|---|--------|-------|------------|
| <b>a. For six points, <math>t = 2.776</math></b>  |        |       |            |
| 12.5  | 3.63   | 0.047 | 1.048      |
| 25.0  | 3.09   | 0.040 | 1.041      |
| 37.5  | 3.00   | 0.039 | 1.040      |
| 50.0  | 3.05   | 0.040 | 1.040      |
| 62.5  | 3.15   | 0.041 | 1.042      |
| 75.0  | 3.27   | 0.042 | 1.043      |
| <b>b. For five points, <math>t = 3.182</math></b> |        |       |            |
| 12.5  | 3.63   | 0.045 | 1.046      |
| 25.0  | 3.09   | 0.047 | 1.049      |
| 37.5  | 3.00   | 0.051 | 1.052      |
| 50.0  | 3.05   | 0.055 | 1.056      |
| 62.5  | 3.15   | 0.058 | 1.060      |
| <b>c. For four points, <math>t = 4.303</math></b> |        |       |            |
| 12.5  | 5.69   | 0.074 | 1.077      |
| 25.0  | 4.67   | 0.061 | 1.063      |
| 37.5  | 4.81   | 0.063 | 1.065      |
| 50.0  | 5.25   | 0.068 | 1.071      |

forming the regression analysis on eq 5. We are still obliged to check the residuals  $\epsilon$  in the logarithmic domain to see whether they are also normally distributed. Then, we can determine whether our experimental answer is statistically acceptable as the right answer with a  $t$ -distribution to test the hypotheses that  $H_0: B = b_0$ , versus  $H_1: B \neq b_0$  based on

$$|B - b_0| > \frac{s t (N - 2, 1 - \alpha/2)}{\left( \sum_{i=1}^N (X - \bar{X})^2 \right)^{1/2}} \quad (9)$$

where  $b_0$  is the correct value of  $b$  in eq 5.

Multiple simulated air tightness measurements demonstrated the effect of normally distributed errors in reading  $Q$  that were bounded within a chosen range of 5, 10 or 20% on either side of the correct value. The simulations also demonstrated the effects of using either 6 or 30 pairs of data each. All simulations were confined to  $12.5 \text{ Pa} < \Delta P < 75 \text{ Pa}$  with 12.5-Pa steps, as prescribed by E 779. In all cases the results, using eq 4 and 5, satisfied the hypothesis that  $B = b$  at the 95% level of confidence.

The model simulated was  $n = 0.75$  and  $C = 1.715$ . Ten simulations of each of the following cases were performed: 5, 10 and 20% normally distributed, unbiased errors in  $Q_{\text{exp}}$  with six sets of data and 10 and 20% normally distributed, unbiased errors in  $Q_{\text{exp}}$  with thirty sets of data. The results are summarized in Table 2. Clearly, lower measurement error and more data pairs improve precision.

The ratios of mean and true values shown in Table 2 indicate that the experiment was not significantly bi-

ased, a potential problem because of the transformation into and out of the logarithmic domain. The coefficients of variation demonstrate that 30 sets of data greatly enhance the precision of any single experiment. Compared to setting up the fan system, taking the  $\Delta P$  and  $Q$  data is not terribly time-consuming. Therefore, E 779 should suggest 30 data sets for those end-use calculations that require more precision than simple comparisons.

The above discussion about confidence limits applies equally to  $L$ , which is different from  $Q$  by a constant, as seen in eq 2a and 2b. The upper and lower bounds of  $L$  would be calculated as in eq 8a.

### Bias in measurements

Some sources of bias for fan pressurization measurements include nonlinear instrumentation, incorrect zeroing of the instrumentation, a superimposed wind pressure, and building leakage sites that have different characteristics, depending on whether the flow is inwards or outwards. E 779 requires both pressurization and depressurization modes of measurement. A separate leakage area is then calculated for each mode, using eq 2. If we postulate that the differences in  $n$  and  $C$ , calculated from pressurization and depressurization measurements, are attributable to a pressure or instrumentation offset, then it is possible to estimate what that offset is from an adaptation of eq 1

$$C_1 (\Delta P + \Delta p)^{n_1} \approx [(C_1 + C_2)/2] (\Delta P)^{(n_1 + n_2)/2} \quad (10)$$

where  $\Delta p$  is the pressure offset, 1 is a subscript for pressurization or depressurization, and 2 is a subscript for the opposite mode, i.e., depressurization or pressurization. Solving eq 10 for  $\Delta p$  gives

**Table 2. Averaged values of  $n$  and  $C$  normalized to the true values of  $n$  and  $C$  for 10 simulated data sets. Sizes of sets ranging between 6 and 30 pairs of  $\Delta P$  and  $Q$  data and for errors ranging between 5 and 20%.  $N$  is the number of data per simulation. The coefficients of variation shown are the square root of the sum of squares of the differences between the regression value and the true value, normalized to the true value, for example  $\{\sum (n_{\text{regr}} - n_{\text{true}})^2 / 10\}^{1/2} / n_{\text{true}}$ .**

| $N$ :   | 6     | 6     | 6     | 30    | 30    |
|---|-------|-------|-------|-------|-------|
| Error (%)   | 5     | 10    | 20    | 10    | 20    |
| $n_{\text{mean}}/n_{\text{true}}$                           | 0.988 | 1.007 | 1.003 | 1.016 | 0.996 |
| Coefficient of variation                                    | 3.4%  | 5.6%  | 10%   | 2.1%  | 2.3%  |
| $C_{\text{mean}}/C_{\text{true}}$                           | 1.022 | 0.955 | 0.961 | 0.955 | 1.005 |
| Coefficient of variation                                    | 9.5%  | 13.0% | 29%   | 5.7%  | 7.2%  |
| $Q_{\text{mean}} (4\text{Pa})/Q_{\text{true}} (4\text{Pa})$ | 1.009 | 0.962 | 0.964 | 0.971 | 1.001 |



$$\Delta p \approx \left\{ \left[ (C_1 + C_2) / 2C_1 \right]^{(1/n_1)} (\Delta P)^{(n_1 + n_2) / 2n_1} \right\} - \Delta P \quad (11)$$

Application of eq 11 to sets of pressurization and depressurization data worked well in comparison to adjusting a constant offset to both sets of data until both  $n$  and  $C$  values are essentially equal. However, calculations of offset for pressurization and depressurization of 13 duplex dwellings during winds that bordered the E 779 upset value of 2 m/s resulted in an average value of  $0.23 \pm 2.12$  Pa standard deviation. Ideally, the average value should be close to 0 Pa and the standard deviation less than 1 Pa.

### MEASUREMENT AND CALCULATION OF $L$ FOR MULTI-ZONE BUILDINGS

E 779 is appropriate for a single-zone building with negligible internal resistance. Duplexes, townhouses and garden apartments, typical of Army housing, offer the problem of air flow through party construction

during a fan pressurization measurement. The following procedures have been designed to account for this problem in each building type. The procedures require up to three fan pressurization apparatuses. Radios, or some other convenient means for communication, are also required.

#### Duplexes

Two apparatuses are required, one for each dwelling unit. When both are pressurized equally, flow is through the exterior envelope only.

#### Townhouses

Three apparatuses are required. Refer to Figure 2 for four adjacent units, which shows the units in sequence as A, B, C and D. First one pressurizes A, B and C. This characterizes air flow directly from units A and B to the outside. Then B, C and D are pressurized to characterize flow from units C and D to the outside. If there are more than four units in a row, then one must leap-frog down the row, guarding each apartment that is being measured with equal pressure from apparatuses in apartments on either side.

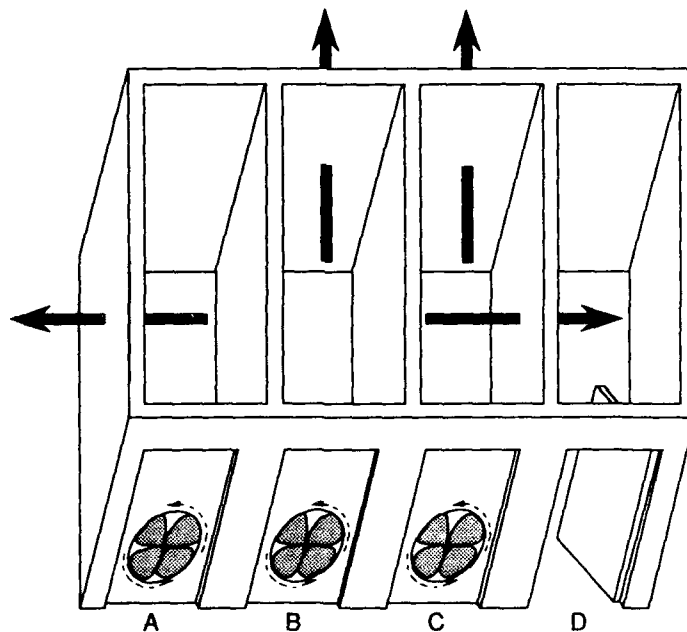


Figure 2. Fan pressurization of a four-plex townhouse. Air blown into units A and B leaves through the envelope, not an adjacent unit, thanks to adjacent fans at the same pressure. Air from guard fan C also leaks into D. Therefore, to measure units C and D, the fan in unit A will be moved to unit D.

The overall leakage area of a four-unit townhouse may be calculated as follows

$$L_{\text{Total}} = L_{\underline{AB}} + L_{\underline{ABC}} + L_{\underline{BCD}} + L_{\underline{CD}} \quad (12)$$

where the subscripts show which units were pressurized and the underline denotes the source of the measurement data.

#### Garden apartments

Refer to Figure 3 for the four-apartment case. This is analogous to the townhouse approach, except that each unit is treated as an interior unit, with two adjacent units. Units that are separated by corners, not planes, like A and D in Figure 3, are assumed to have negligible interzonal flow from one to the other. Unlike townhouses, there is no equivalent of an end. The overall leakage area of a four-unit townhouse may be calculated as follows

$$L_{\text{Total}} = L_{\underline{ABD}} + L_{\underline{ABC}} + L_{\underline{BCD}} + L_{\underline{ACD}} \quad (13)$$

#### MEASUREMENT AND CALCULATION OF $L$ FOR PARTY WALLS AND FLOORS

The equivalent leakage area across a party wall or floor can be about the size of the errors in calculating  $L$

for the exterior envelope of a zone. Two methods to determine interzonal leakage areas were attempted in this study: 1) performing tests with and without a guarding pressure in the adjacent zone of interest and subtracting the resulting equivalent leakage areas, and 2) employing two fan pressurization apparatuses in concert in the adjacent zones such that one provides a constant reference pressure across the zonal boundary and is the source of flow readings and the other is adjusted to provide a series of pressure differences across the zonal boundary. Feustel (1990) discusses these two techniques, but does not discuss the resulting confidence intervals. He advocates the latter method for determining interzonal air permeability.

Let's look at the measurement protocols for these two methods, which we call the zone difference method and the pressure difference method.

#### Zone difference method

This technique requires accurate measurement of pressures and flows. Sufficient repetitions of the pressure and air flow readings can suffice to accomplish the desired precision of measurement. However, if the instrumentation is biased, as is common with commercial pressure gauges used in fan pressurization apparatuses, the results may be erroneous. The equivalent leakage area between zones B and C,  $L_{B-C}$ , is obtained as follows

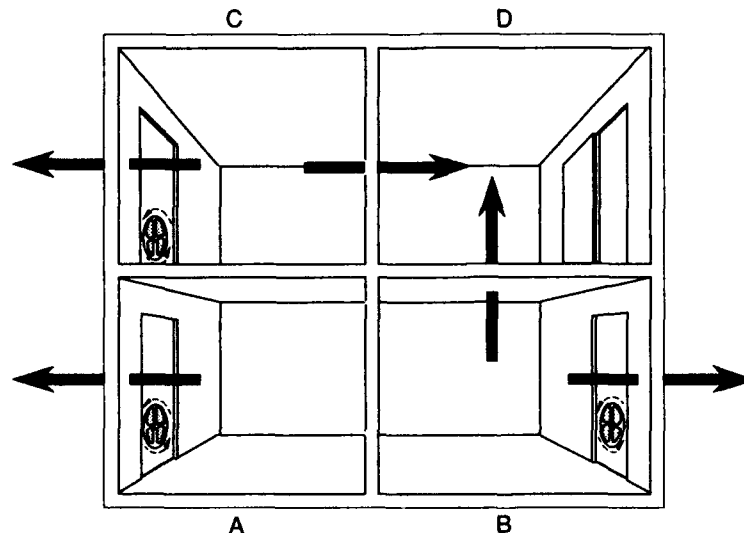


Figure 3. Fan pressurization of a four-plex garden apartment. Air blown into unit A leaves through the envelope only, not an adjacent unit, thanks to guard fans at the same pressure. Air from guard fans B and C also leaks into D. Therefore, to measure the other units (B, C and D) a fan will be placed in adjacent units.

$$L_{B-C} = L_{AB} - L_{ABC} \quad (14)$$

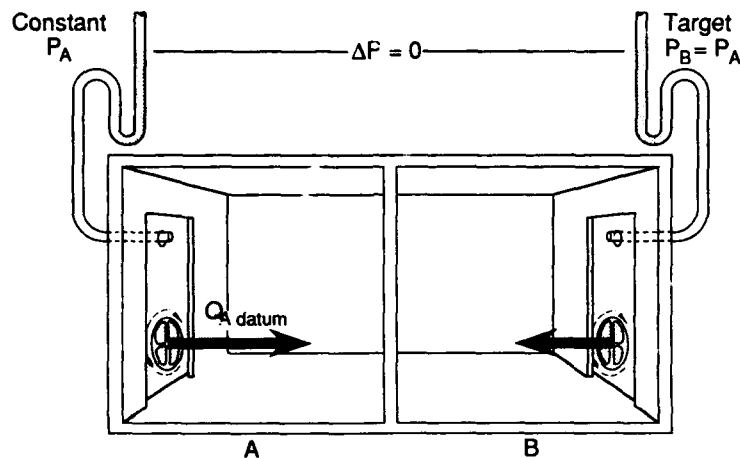
where readings are obtained at zone B with all adjacent zones pressurized and the  $L_{ABC}$  subtracted from the  $L_{AB}$  obtained with zone C open and unpressurized, but with the other zones adjacent to B pressurized at the same level as B.

#### Pressure difference method

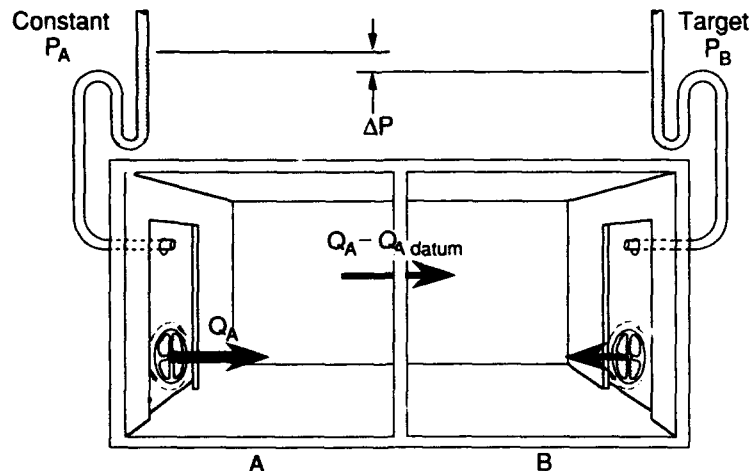
This technique directly measures flows and pressures with differences between a datum value for each quantity and values that result from adjusting the two

apparatuses as follows (refer to Fig. 4): apparatus A is maintained at a constant pressure and flows are noted each time the pressure at apparatus B is adjusted. With apparatuses A and B at equal pressures, a datum flow level is established on apparatus A. The pressure at apparatus B is dropped by stages to establish a target  $\Delta P$  across the party wall or floor. At each stage the resulting flow is read on apparatus A and subtracted from the datum value, then  $C$  and  $n$  are calculated by performing a regression from eq 15.

$$(Q_A - Q_{A \text{ datum}}) = C (P_A - P_B)^n \quad (15)$$



a. Initially, units A and B are pressurized at the same reference pressure  $P_A$ , in order to establish  $Q_{A \text{ datum}}$  on apparatus A.



b. Subsequently, the pressure in unit B is set to obtain a target  $\Delta P$ , with  $P_A$  held constant. The flow across the party wall is  $Q_A - Q_{A \text{ datum}}$ .

Figure 4. Fan pressurization of a party wall.

where  $Q_{A \text{ datum}}$  is determined initially with zones A and B pressurized equally,  $P_A$  is a constant value maintained in zone A,  $P_B$  is varied in zone B, and  $Q_A$  is measured in zone A.

#### AIR TIGHTNESS MEASUREMENTS IN MULTIPLEX HOUSING

In June 1988 and November of 1989, fan pressurization measurements of air tightness were made in buildings at Fort Drum, New York. Measurements were

made in family housing duplexes, townhouses and garden apartments, as seen in Figure 5. The procedure generally followed E 779, except that multiple fan units were in use to provide equal pressure levels in adjacent units. In 1989 the  $\Delta P$  intervals were chosen to be evenly spaced in the log domain, approximately as follows: 14.9, 17.4, 19.9, 23.6, 27.4, 32.4, 37.3, 43.6, 51.0 and 59.7 Pa.

##### Duplex housing units

Five duplex family housing units were measured with fan pressurization devices to characterize the envelope tightness. The resulting leakage areas, calculated



*a. Duplex.*

*b. Garden apartment.*

*Figure. 5 Multiplex dwellings typical of those that were evaluated for air tightness at Fort Drum, New York.*

**Table 3. Calculated equivalent air leakage areas at  $\Delta P = 4$  Pa in duplex houses at Fort Drum, New York. Buildings 1-3 were measured in June 1988 and buildings 4-5 were measured in November 1989.**

| Building | Unit | Surface (m <sup>2</sup> ) | L (m <sup>2</sup> ) | L per unit of envelope (10 <sup>-4</sup> ) |
|----------|------|---------------------------|---------------------|--|
| 1        | 7533 | 274.0                     | 0.0774              | 2.85                                       |
|          | 7535 | 274.0                     | 0.0433              | 1.58                                       |
| 2        | 7682 | 119.3                     | 0.0635              | 5.32                                       |
|          | 7684 | 119.3                     | 0.162               | 13.6                                       |
| 3        | 7874 | 156.5                     | 0.0438              | 2.80                                       |
|          | 7876 | 156.5                     | 0.0392              | 2.51                                       |
| 4        | 3195 | 216.3                     | 0.0445              | 2.06                                       |
|          | 3196 | 216.3                     | 0.0449              | 2.08                                       |
| 5        | 3205 | 216.3                     | 0.0467              | 2.16                                       |
|          | 3206 | 216.3                     | 0.0441              | 2.04                                       |

for 4 Pa as described above, are shown in Table 3. In the last column, the equivalent leakage areas have been normalized to the area of the exterior envelope, excluding party walls and floors, so that comparisons are possible. Except for the second building shown, these buildings have relatively consistent equivalent leakage areas per unit of exterior envelope.

#### Four-plex housing units

One four-plex of family housing units had a common stair-entry-storage area that divided two single-floor apartments on each of two floors. Therefore, the building could be treated as two duplexes, arranged vertically, ignoring the unheated central circulation areas. The results, calculated according to eq 12, are shown in Table 4.

**Table 4. Calculated equivalent air leakage areas at  $\Delta P = 40$  Pa in four-plex units numbered 446 A and B, and C and D.**

| Location | Unit | L (m <sup>2</sup> ) | L per unit of envelope (10 <sup>-4</sup> ) |
|----------|------|---------------------|--|
| Down     | A*   | 0.0280              | 2.62                                       |
|          | B*   | 0.0303              | 2.84                                       |
| Up       | C†   | 0.0527              | 2.34                                       |
|          | D†   | 0.0460              | 2.04                                       |

\*106.7-m<sup>2</sup> surface area each on the first floor.  
†225.0 m<sup>2</sup> on the second floor.

Other four-plex family housing units had separate ground-level entrances for the four single-floor garden apartments, which were arranged with two on each of two floors. The equivalent leakage areas were calculated according to eq 13. Results from this type of apartment are shown in Tables 5 and 6.

Another building had no internal stairs. External stairs led to exterior balconies in front of garden apartments. The equivalent leakage areas were computed according to eq 13, and are shown in Table 7.

#### Discussion

The apartments evaluated in Table 5 were the source of the most complaints about winter discomfort. These apartments had the highest *L* per unit of envelope of those tested, except for 7684 (Table 3). Infrared thermography revealed no improperly installed insulation, but showed significant air leakage around doors, windows and under shoe plates on walls. The normalized values of *L* show little difference between upstairs and down, although downstairs has only wall for the exterior envelope, whereas the upstairs has ceiling, as well. An equivalent leakage area of less than  $2.5 \times 10^{-4}$  per unit of envelope appears to be a readily achievable standard for both ceiling and wall, as Tables 3 and 4 demonstrate. Tables 6 and 7 indicate that for those buildings exterior ceilings were constructed to be more airtight than exterior walls.

There was a question whether the *L* across party walls and floors was significant enough to warrant using guard pressurization in adjacent units. Several fan pressurizations were run in multiplex units with and without guard pressure. The *L* obtained without guard pressure was typically 30 to 50% higher than that obtained with guard pressure. This indicated that in these buildings, at least, guard pressure was necessary for obtaining the *L* for the building envelope.

**Table 5. Calculated equivalent air leakage areas at  $\Delta P = 4$  Pa in four-plex units numbered 917 A and D, and B and C. The data were obtained in 1988.**

| Location | Unit | L (m <sup>2</sup> ) | L per unit of envelope (10 <sup>-4</sup> ) |
|----------|------|---------------------|--|
| Down     | A*   | 0.149               | 6.17                                       |
|          | D*   | 0.193               | 7.99                                       |
| Up       | B†   | 0.179               | 7.18                                       |
|          | C†   | 0.188               | 7.54                                       |

\*241.5-m<sup>2</sup> surface area each on the first floor.  
†249.2 m<sup>2</sup> on the second floor.

**Table 6. Calculated equivalent air leakage areas at  $\Delta P = 4$  Pa in four-plex units numbered 3223 and 3225, and 3224 and 3226. The data were obtained in November 1989.**

| Location | Unit  | L (m <sup>2</sup> ) | L per unit of envelope (10 <sup>-4</sup> ) |
|----------|-------|---------------------|--|
| Down     | 3223* | 0.0340              | 5.52                                       |
|          | 3225* | 0.0320              | 5.20                                       |
| Up       | 3224† | 0.0477              | 2.21                                       |
|          | 3226† | 0.0294              | 1.36                                       |

\*61.6-m<sup>2</sup> surface area each on the first floor.

†215.6 m<sup>2</sup> on the second floor.

**Table 7. Calculated equivalent air leakage areas at  $\Delta P = 4$  Pa in four-plex units numbered 9631 A and B, and C and D. The data were obtained in November 1989.**

| Location | Unit | L (m <sup>2</sup> ) | L per unit of envelope (10 <sup>-4</sup> ) |
|----------|------|---------------------|--|
| Down     | A*   | 0.0268              | 2.14                                       |
|          | D*   | 0.0315              | 2.52                                       |
| Up       | B†   | 0.0326              | 1.47                                       |
|          | C†   | 0.0268              | 1.21                                       |

\*125.0-m<sup>2</sup> surface area each on the first floor.

†221.7 m<sup>2</sup> on the second floor.

**Table 8. Calculated equivalent air leakage areas at  $\Delta P = 4$  Pa between units.**

**a. Results obtained in 1988 by zone difference method**

| Pressured | Open | Party wall (m <sup>2</sup> ) | L (m <sup>2</sup> ) | L per unit of wall (10 <sup>-4</sup> ) |
|-----------|------|------------------------------|---------------------|--|
| 7533      | 7535 | 32                           | 0.0248              | 7.75                                   |
| 7535      | 7533 | 32                           | 0.0322              | 10.1                                   |
| 7682      | 7684 | 32                           | 0.0423              | 13.2                                   |
| 7684      | 7682 | 32                           | 0.1160              | 36.3                                   |
| 7874      | 7876 | 32                           | 0.0649              | 20.3                                   |
| 7876      | 7874 | 32                           | 0.0020              | 0.64                                   |

**b. Results obtained in 1989 by pressure difference method**

| Monitored | Varied | Party wall (m <sup>2</sup> ) | L (m <sup>2</sup> ) | L per unit of wall (10 <sup>-4</sup> ) |
|-----------|--------|------------------------------|---------------------|--|
| 3223      | 3225   | 13.8                         | 0.00440             | 3.19                                   |
| 3226      | 3224   | 13.8                         | 0.00470             | 3.41                                   |
| 9631C     | 9631D  | 18.2                         | 0.00596             | 3.27                                   |

## AIRTIGHTNESS MEASUREMENTS OF PARTY WALLS AND FLOORS

Determination of  $L$  for party walls and floors was done by two means: using the zone difference method described in eq 14 (this method was used in 1988) and using the pressure difference method described in eq 15 (this method was used in 1989). Table 8 illustrates  $L$  and  $L$  per unit of party wall between dwellings through party walls in units reported on in Tables 3 through 7.

Table 9 illustrates  $L$  and  $L$  per unit of party floor between dwellings through party floors in units reported on in Tables 3 through 7. In the three buildings measured by the pressure difference method, the  $L$  per unit of party floor area was an order of magnitude below that for party walls.

The consistency of results from the data for  $L$  per unit area of envelope that resulted from the pressure difference method strongly suggests that it is more reliable than the zone difference method, as will be discussed in the following section. The absolute values of  $L$  obtained by the pressure difference method are about one tenth of those obtained for the exterior envelope. This is the same order of magnitude as the errors expected, as discussed above under *Confidence Intervals*, above. Therefore, the  $L$  values obtained by the zone difference method are questionable.

When one translates the confidence limit out of the log-log domain in which the regression was performed, one obtains a factor by which to multiply or divide the modeled value of  $Q$  or  $L$  at a given pressure. For guarded pressurization measurements of individual zones that tested the tightness of the exterior envelope only, such confidence factors ranged from a minimum of 1.0675 to a maximum of 1.204. In contrast, for interzonal measurements the confidence factor ranged from a minimum of 1.43 to a maximum of 5.52. In the latter case, for example,  $L^+(4 \text{ Pa}) = 5.52 \times L(4 \text{ Pa})$  and  $L^-(4 \text{ Pa}) = L(4 \text{ Pa})/5.52$ .

**Table 9. Calculated equivalent air leakage areas at  $\Delta P = 4$  Pa between units through party floors in units reported on in Tables 6 and 7. Results obtained in 1989 by pressure difference method.**

| Monitored | Varied | Party floor (m <sup>2</sup> ) | L (m <sup>2</sup> ) | L per unit of floor (10 <sup>-4</sup> ) |
|-----------|--------|-------------------------------|---------------------|---|
| 3223      | 3224   | 107.7                         | 0.00281             | 0.261                                   |
| 3226      | 3225   | 107.7                         | 0.00187             | 0.174                                   |
| 9631A     | 9631C  | 106.2                         | 0.00416             | 0.392                                   |

## CONCLUSIONS

The E 779 technique for determining airtightness of single-zone buildings can be adapted to multiplex buildings, using guard pressurization from apparatuses in adjacent units, if the goal is simply to characterize the leakage characteristics of the exterior envelope. One need only pressurize adjacent apartments and add up the equivalent air leakage areas obtained. However, if one wishes to characterize the equivalent air leakage areas *between* units, many more data pairs, using the pressure difference method, are required to establish the required precision. Thirty pairs of pressurization and air flow data would be appropriate.

The E 779 technique has potential experimental errors inherent that may result in autocorrelation of the data. The operator of the apparatus is likely to use sequential test pressures. This may allow bias because of wind pressure changes. The installation of the apparatus can influence the results, depending on the variability of seals in the apparatus from setup to setup. Ideally, the experimental sequence that determines which  $\Delta P$  to use should be the result of a randomized plan in order to avoid autocorrelation between the data sets. This would at least help offset the effect of variable induced wind pressures on the building.

Uncontrolled errors that result from setting up the apparatus would best be controlled by removing the apparatus from the door and reinstalling it between obtaining each data pair. E 779 would benefit from experimentation that would demonstrate the error that potentially results from such factors as flaws in seals, imprecise instruments, etc. A set of controlled experiments using the calibration procedure in standard test method E 1258 (ASTM 1988) would be useful for any given type of E 779 apparatus.

The fan pressurization experience with multiple units indicates that there is reasonable consistency between units within a single contractor's development. They also demonstrate that one cannot ignore the air tightness between units. Therefore, simultaneous pressurizations with guard fan pressurization apparatuses are required to equalize pressure between units.

A tentative conclusion would tie  $L$ /unit area to comfort. If one compares the values for Table 5 with those in Tables 3, 4, 6 and 7, one might conclude that values of  $L$ /unit area below  $5 \times 10^{-4}$  cause relatively few complaints among occupants in family housing at Fort Drum, whereas values above  $7 \times 10^{-4}$  are likely to result in complaints.

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